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Processing Deficits in Monitoring Analog and Digital Displays: Implications for Attentional Theory and Mental-State Estimation Research

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Abstract

Subjects performed short term memory tasks, involving both spatial and verbal components, and a visual monitoring task involving either analog or digital display formats. These two tasks (memory vs. monitoring) were performed both singly and in conjunction. Contrary to expectations derived from multiple resource theories of attentional processes, there was no evidence that when the two tasks involved the same cognitive codes (i.e., either both spatial or both verbal/linguistic) there was more of a dual task performance decrement than when the two tasks employed different cognitive codes/processes. These results are discussed in terms of their implications for theories of attentional processes and also for research in mental state estimation.

Introduction

There has recently been considerable interest in assessing the patterns of interference effects obtained when operators simultaneously perform two or more tasks that require controlled information processing. It is commonly assumed that as the total amount of attention (or 'capacity' or 'mental resources') required to perform these tasks increases above some level, overall performance levels will decrease. This performance decrement is often assumed to follow the principle of graceful degradation outlined by Norman and Bobrow (ref. 1). Our research is directed towards the general goal of identifying performance deficits in dual-task situations involving tasks similar to those performed by operators in advanced flightdeck environments. Our interest, however, is not so much simply in the fact that performance in these situations falters when the operator is overloaded. Rather, we are primarily interested in determining the specific ways in which performance is affected when the total task demands exceed the limited information processing capabilities of the operator. For example, if a pilot cannot accurately read the information displayed on a CRT, what perceptual/cognitive processes are responsible for this performance decrement?

Due to the complexity of many of the tasks performed within the aerospace flight deck environment, there are many ways in which performance could be affected. If our goal is to determine how various <u>mental states</u> (e.g., boredom, fatigue) are related to performance within these complex environments,

then it is essential that we have an in-depth understanding of the factors that influence operators' behaviors in these situations. To foreshadow a bit, we would argue that the efforts to a) identify mental states using physiological indices and b) relate these mental states to performance in the flight deck environment can succeed only if we possess a concise knowledge of the cognitive processes affected by task demands.

The research in this article had several inter-related goals. The first was to attempt to determine the optimal format for presenting information to operators in a process control task. The process control task we employed exhibited two characteristics that make it similar to tasks performed by flightdeck personnel. First, there were a large number of display indicators that the subjects monitored. Second, although the subject was required to monitor all of the indicators, a response was required only when one of the indicator values exceeded the acceptable range. This latter task characteristic is analogous to when a pilot takes corrective action only when the actual airspeed deviates by a certain amount from the desired, or target, airspeed.

Our second goal was to examine how different types of display formats affect operators abilities to perform other ongoing activities. Towards this end we attempted to apply existing theories of attentional processes to predict performance levels in a dual task situation. Finally, we hoped that the results of this research would enable us to develop reasonable tasks for use in mental state estimation research.

We will review the information relevant to these three goals after first briefly describing the general approach taken in our research. To provide some insight into which factors affect performance in ongoing visual monitoring tasks, we employed a dual-task methodology (cf., ref. 2) that has proven useful to researchers investigating memorial and attentional processes in a variety of basic (e.g., refs. 3, 4, 5, 6) and applied (e.g., refs. 7, 8, 9) research settings. Although we describe the dual task method in detail when we present our main experiment, the basic logic behind this method is as follows. An operator is required to perform two tasks, both singly and in conjunction, with performance being measured in both the single and dual task conditions. One task is designated the primary task and the operator is instructed to attempt to maintain optimal performance on this task. Assuming that performing the two tasks concurrently exceeds the limited information processing capacity of the operator, performance levels on the secondary task can be used as an indirect estimate of the amount of capacity, or processing resources, required by the primary task. By varying the difficulty level of the primary and secondary tasks we can examine performance

across a range of performance conditions. (See refs. 10 and 11 for a detailed description of the application of the dual task methodology.) In addition, we can investigate how different versions of these tasks fare when performed in conjunction with other tasks from real-world multi-task situations.

One final point regarding our general research strategy. We made a deliberate attempt in our study to investigate theoretically important issues using tasks that have relevance to performance in real world situations. We believe that as a general research strategy this approach helps to increase the applicability of the research (and thus aids the human factors specialist), and also allows the basic researcher to address theoretical issues under highly controlled laboratory conditions.

Attentional Limitations in Performing Controlled Information Processing Tasks

Our research relied heavily upon current models and theories of human attentional processes. In this section we briefly review these models and theories. The reader should note that this review is not intended to be inclusive, as several excellent reviews exist in the literature (e.g., refs. 10 and 12). (Readers already familiar with modern theories of attention can go directly to the descriptions of the present research.)

It almost goes without saying that in everyday life people are often engaged in tasks that require them to perform two or more functions simultaneously (e.g., driving a car while attempting to locate a specified street address). The literature on attentional processes and information processing is replete with cases in which human performance suffers when a person is required to perform two or more tasks concurrently (e.g., refs. 13, 14). There are also cases in which such time-sharing is carried out quite efficiently (e.g., refs. 15, 16). One of the puzzles facing theorists and researchers over the last 20 to 30 years has been to specify under what conditions two tasks may be time-shared efficiently (e.g., walking while talking) and under what other conditions time sharing is inefficient (e.g., carrying on a conversation while reading).

Historically, there have been two general approaches towards providing a theoretical explication of such time-sharing phenomena. In the 1950s and 1960s there were a number of investigations showing that humans were extremely limited in their ability to attend to two separate auditory messages (e.g., refs. 17, 13, 14). Findings such as these lead to the development of structural theories (e.g., refs. 17, 3, 18) that attempted to identify at which point in the processing

of information did the "bottleneck" occur that seemed to limit performance in dichotic listening experiments, as well as in other cases in which people showed limitations in their ability to process information efficiently (e.g., the psychological refractory period phenomena; see ref. 19 for a review). According to these structrural theories, then, the degraded performance one observes when the operator attempts to process large amounts of information is attributable to the manner in which the information processing stages are "structured" or configured.

An alternative approach to explaining time-sharing was offered by the capacity theories proposed in the 1960s and 1970s (e.g., refs. 20, 21). This approach is best exemplified by Kahneman's theory in which he proposed that there exists a single, limited "pool" of capacity that can be allocated to performing all ongoing controlled information processing tasks. According to this view, the limitation in time sharing is not one of limited access to processing structures, but rather it is that the processing structures can only function when "capacity" is allocated to those structures. The efficiency with which two tasks may be time shared depends upon the availibility of sufficient capacity to perform the necessary information processing. If there is adequate capacity to meet the demands of the two tasks, then these tasks may be performed as efficiently in conjunction as they can be performed singly; if the total capacity required by the two tasks exceeds the "pool" of available capacity, then performance in the dual task condition will fall below what is observed in the single task conditions.

Although both structural and capacity theories are capable of explaining a great deal of the data on time sharing, there are numerous findings that indicate that these theoretical conceptualizations are too impoverished to provide a complete explication of the phenomena of interest. (For a review of these difficulties, see refs. 22 and 12.) As a result, there has recently been proposed a third approach to time sharing, namely resource theory (e.g., ref. 22). Resource theory has been successfully applied in a number of investigations, including basic research (e.g., refs. 23, 24, 25) and applied human factors research (e.g., refs. 7, 26). This approach to understanding human cognitive abilities appears to have great promise, although there have been some arguments made against theories that propose the existence of multiple resources (e.g., ref. 27). Since our research utilizes a resource theory approach, we will describe the general concepts embodied in multiple resource theory in some detail.

Navon and Gopher (ref. 22) proposed that instead of a single pool of capacity that may be shared among various processing structures, it might be better to envision the human

cognitive system as being comprised of a limited number of processing "resources". Capacity and resources are both hypothetical constructs that are used to refer to underlying commodities that enable a person to perform some task(s). A major difference between the concepts of capacity and resources is that capacity is generally assumed to be rather amorphous, in the sense that it may be allocated to any processing stage or structure, whereas resources are less general in nature. That is, it is assumed that resources may only be allocated to specified processes or subprocesses. It is further assumed that several types of resources exist and these differ in kind, such that they may not be readily substituted for one another. (Multiple resource theories do allow for some substitution of resources. However, there is generally a loss of processing efficiency associated with these substitutions; we will return to the issue of processing efficiency momentarily.)

Recall that capacity theory assumed that a) there was a single pool of capacity, and b) that, in a dual task situation, if there were spare capacity left from performing Task A, then that "spare" capacity could be allocated to performing Task B. Multiple resource theory, on the other hand, suggests that if Task B requires a particular resource that is in short supply, then even if other resources are readily available (e.g., those resources not required to perform Task A), these other resources can not be utilized efficiently in performing Task B.

As mentioned previously, multiple resource theory assumes that differing resources are differentially efficient when applied to processes or subprocesses. Efficiency here is used in the econometric sense of marginal efficiency (i.e., the change in performance level observed when one unit of a resource is added to or removed from a process). Finally, different tasks require differing resources for the processing involved in that task to be completed. The resources required to perform a task is generally referred to as that task's resource composition.

To summarize according to multiple resource theories, the following factors are assumed to affect performance in single and dual task situations: (a) the resource composition(s) of the task(s) under investigation, (b) the amount of each resource type available to be allocated to the task(s), and (c) the relative efficiency of the resources allocated to the task(s). One obvious difficulty with an unconstrained multiple resource model is the issue of how one determines <u>a priori</u> precisely what constitutes a resource and which of these putative resources are required to perform specified tasks. Without appropriate limitations, resource theory could follow in the path of instinct theory and faculty psychology and propose resources <u>ad infinitum</u>. There are

however, two promising approaches for limiting the number and type of resources incorporated in the models.

One approach to the problem of identifying resources is to view each cerebral hemisphere as having its own processing resources. This perspective draws heavily upon findings indicating that the two hemispheres are specialized for performing different functions (e.g., spatial tasks are assumed to rely upon right hemisphere resources, verbal tasks are assumed to rely upon left hemisphere resources). There is considerable empirical support for this general approach to resource theory (e.g., refs. 23, 24, 28, 29, 30, 31, 26,32).

A second approach to attempting to limit the proliferation of processing resources is best exemplified by the work of Wickens (ref. 33). This approach examines the types of tasks that produce interference effects when performed in conjunction and then uses these data to discern the specific types of tasks that utilize similar resources. The general underlying assumption here is that if two tasks interfere with one another when performed in conjunction, then these tasks must employ the same or similar resources; if there is little or no dual-task interference then the resource compositions of the two tasks overlap only minimally.

Using this approach, Wickens (refs. 33, 12) has identified the following as candidates for processing resources: (a) the type of input and output modality (e.g., visual vs. auditory stimuli; manual vs. vocal responses), (b) the code or representational format utilized by the subject (e.g., a verbal/linguistic code vs. a spatial code), (c) the stage of processing (e.g., encoding, central processing and response selection, response execution), and (d) the hemisphere of processing (cf. the distinctions noted above in the first approach). The present research employed the distinction between verbal/linguistic codes vs. spatial codes in an effort to apply multiple resource theory to a real world information processing task.

Application of Attentional Theory to a Visual Monitoring Task

As indicated previously, our research is couched within the framework provided by multiple resource theory. One of our major goals was to examine the patterns of interference effects obtained in dual task conditions when subjects perform visual monitoring tasks. According to multiple resource theory, the pattern of performance observed in a dual task situation depends upon the resource composition of the primary and secondary tasks. According to this view, then, it is possible for two tasks that have very different resource compositions to show different levels of dual task performance as a function of the secondary task with which they are conjoined. That is, a

task that has a large spatial processing component may produce large dual task performance decrements when conjoined with a secondary task that also utilizes spatial codes but shows little or no dual task decrement when conjoined with a secondary task that utilizes verbal/linguistic codes.

If the concept of multiple resources (as defined by the nature of the codes involved in the processing tasks) is accurate, then this has implications for the design of displays for person-machine systems. For example, if an operator is performing a series of tasks that are highly spatial in nature (e.g., flying an aircraft), then the use of displays that rely heavily upon spatial processes may not be optimal. In this case it may be better to use displays that require verbal/linguistic processes. To test this hypothesis, we employed a laboratory analog of a process control task originally described by Hanson, Payne, Shively and Kantowitz (ref. 9).

Hanson et al (ref. 9, Experiment 2) required subjects to monitor either an analog or a digital display presented on a cathode ray tube (CRT). In both display formats there were indicators that presented data corresponding to the constantly varying outputs of a simulated process control system. The subject's task was to monitor the system outputs and take a corrrective action whenever one of the displays went beyond a specified range. In the analog condition the system output values were represented by the length of the lines in a display similar to a histogram. In the digital display condition the actual numerical value of each system variable was presented. Coupled with this visual monitoring task was either a 2- or 4-choice auditory choice reaction time task. These reaction time tasks were included in order to assess the processing demands of the analog vs. digital displays. Results showed that increasing the difficulty level (operationalized as the number of display indicators presented) of the analog displays had little effect on performance in the auditory choice reaction time task but had a sizable impact on performance when subjects were monitoring the digital displays. Hanson et al interpreted their results within a single capacity framework, arguing the the analog task required less capacity to perform and this then resulted in less performance decrement as the secondary task difficulty was increased.

Our research was designed as a follow-up to the study by Hanson et al (ref. 9). We presented subjects with two tasks, a short term memory task and either a digital or an analog visual monitoring task similar to those used by Hanson et al. For both of these tasks (memory and monitoring), we constructed one version of the task that relied predominately upon spatial codes/processes and a second that relied upon verbal/linguistic codes/processes.

Our first experiment was a pilot study designed to establish appropriate task parameters for the memory task in the main experiment. This pilot study also provided information regarding the processing requirements of the short term memory tasks. In the pilot study subjects viewed a computer monitor containing a four x four (16 cell) matrix. Three letter English words were presented one at a time within single cells of the matrix using a three sec presentation rate and a 1 sec interstimulus interval. For different trials, the instructions for the memory task were intended to tap either spatial processing, verbal/linguistic processing, or a combination of these two types of processes.

Across trials, subjects were presented with lists of varying length (range = 4 - 9 items) and were given one of three recall tasks. In the item condition, subjects were instructed to recall only the items from the target list. On the location trials the subjects' task was to remember the locations within the matrix that contained items during the list presentation. Finally, in the item + location + order condition subjects were required to place the items they recalled in the correct locations within the matrix and also indicate the serial order with which these items appeared in the list. We assumed that the item task loaded primarily upon verbal/linguistic codes (or processes), the location task loaded primarily upon spatial codes/processes, and that the item + location + order task tapped both types of processes.

In addition to studying the lists, subjects in the pilot experiment were also given one of three tasks to perform between the end of list presentation and the start of the recall test. In the spatial interpolated task subjects were presented with pairs of symbols (e.g., ####, &&&&) in different locations on the CRT screen and were asked to decide if these items were in certain spatial arrangements (e.g., 'Is the #### above the &&&&?'). These items appeared in sequential pairs, with the direction corresponding to the above or below decision being indicated before the two comparison stimuli were presented. Subjects indicated their decisions by pressing buttons on a response box in front of the CRT. The second interpolated task was a numerical decision task analogous to the spatial task. Subjects were given a 'direction' (greater than, less than), followed by two successive three-digit numbers. The subjects' task was to decide if the two items were in the designated numerical relations. Finally, in the Brown-Peterson task subjects were given a three digit number and asked to count backwards out load by threes from that number as rapidly as possible. Each of these tasks lasted for 60 sec with the recall tests being given immediately after the interpolated tasks.

The results of this pilot study indicated that, not surprisingly, recall performance was affected by list length, with more items being recalled as list length was increased. More importantly, the comparison of the several combinations of recall task x interpolated activity offered support for the notion that the item and location recall tasks were differentially affected by the interpolated tasks. First, the Brown-Peterson task, which requires subjects to keep a mental tally of the current numeric item, subtract 3 from that item and then repeat the entire process over again, produced the lowest recall levels of any of the three interpolated tasks. Also, there was some evidence that the item and location recall tasks were diffentially affected by the spatial and numerical interpolated tasks. Finally, the item + location + order condition produced far lower performance levels than the other two recall condition.

Taken together then, these pilot results indicate that the memory task is sensitive to the memory load; the item + location + order condition imposed the greatest memory load and also produced the lowest recall levels. Furthermore, the spatial, numerical, and Brown-Peterson tasks produced differential degrees of within-trial interference in the item, location, and item + location + order conditions. This latter finding supports our conjectures about the codes/processes involved in these memory tasks. Finally, the results of the pilot study indicated that, for the stimulus items and presentation conditions used in the main experiment, a six item list would produce performance levels in the range of 50% to 95% correct recall, depending upon the recall task. With these findings in hand we proceeded to the main experiment.

Method

Subjects and Design. Eighteen male and 18 female undergraduates at SUNY - Binghamton participated in partial fulfillment of a course requirement for research experience or library research. Of each same-sex group of 18 subjects, 6 were left handed and 12 were right handed, with handedness being determined by subjects self-report and preferred writing hand.

Subjects participated in three 9-trial blocks, two single task blocks (Blocks 1 and 3) and one dual task block (Block 2). In the single trial blocks there were six memory task trials followed by three visual monitoring task trials. In these single trial blocks order of presentation of the three types of memory tasks (item, location, and item + location + order) was counterbalanced across subjects such that each subject received one of each type of memory task in trials 1 - 3 and a different order of these three memory tasks in trials 4 - 6. Each trial consisted of a different set of 6 items and across subjects the same items were presented on each trial and thus each set of

six memory items/locations appeared equally often in each memory condition. Following the six memory task trials there were three visual monitoring trials. Blocks 1 and 3 were identical, with the exception that a different set of memory items was used in each block.

In Block 2 subjects were presented with nine trials in which they performed both the memory task and the visual monitoring task. The nine trials were broken into three sets of three trials each. Each of the three triads contained one of each of the three memory tasks (i.e., item, location, and item + location + order). Across the three triads the order of memory tasks within a triad was counterbalanced using a Latin square design.

One half of the subjects (nine males and nine females) performed a digital visual monitoring task and the remaining subjects performed an analog monitoring task. Within each set of nine same-sex subjects assigned to each type of monitoring task, three were left handed and six were right handed. Thus the between subjects factors in this experiment were type-of-visual-monitoring task (analog vs. digital), sex, and handedness. (These latter two subject variables were included to address issues unrelated to the primary goals of the present study and hence will not be described any further in this report.) The within subjects factors were type of trial (single task vs. dual task) and type of memory task (item, location, item + location + order) on the single task memory trials (trials 1 - 6 of Blocks 1 and 3) and dual task trials (Block 2).

Procedure. Both the short term memory task and the visual monitoring task were controlled by an Apple IIe microcomputer equipped with an Apple color monitor, a millisecond timer and an eight key response box. For the short term memory task subjects viewed a 16 cell (4 x 4) matrix on the computer monitor. A trial consisted of presenting 6 three letter English words, with each word appearing in a different, randomly determined location within the 16 cell matrix. Words were presented at a three sec presentation rate with a one sec interstimulus interval. The same presentation format was used with each of the three memory tasks, with the sole difference between tasks being the instructions given to subjects prior to the trial and the corresponding differences in the retention measures. For the item trials subjects were given standard free recall instructions indicating that their task was to study the items so that they could recall the items from the study list in any order they choose. On the location trials subjects were told that they were not responsible for remembering the actual items that were presented but rather they would be asked to recall which of the cells contained a word during the list presentation. For item + location + order trials subjects were

told that they were to try to remember the items, the locations within the matrix that each item appeared and also the serial presentation order (i.e., first, second, ... sixth) of the items. After these instructions were given subjects were presented with the six target items for that trial. In the single task item trials, after the list was presented, subjects wrote the target items on a sheet of blank paper. In the item and item + location + order conditions, after the list was presented subjects were given a sheet of paper with a 4 x 4 matrix printed on it and were asked to recall the information that they had been instructed to memorize on that trial. On location trials subjects were asked to place an X in each cell of the matrix in which a word had appeared during the list presentation. For item + location + order trials subjects were told to write the items in the cells in which they had appeared and also indicate the order of appearance by numbering the cells from 1 to 6. Subjects were given as much time as needed to complete the tests.

In the single task visual monitoring trials subjects viewed either an analog or a digital display. Both types of displays presented eight indicators representing the status of simulated system outputs. The subject's task was to monitor the eight indicators and "reset" any indicator (by pressing a button on the response box) that exceeded preset boundaries. For the digital displays, the value of each indicator was presented in the center of a box and the upper (282) and lower (110) limits for these indicators were printed above and below the box containing the indicator value (see Figure 1). At the onset of the trial, each indicator started near the middle of the range of acceptable values and began either consistently increasing or decreasing. The software that controlled the monitoring task "updated" each indicator in succession, recorded when the indicator value first exceeded the upper or lower boundary, when the subject "reset" each indicator, and also any "resets" that the subject attempted before the indicator had exceeded its boundary. Once the trial began, each indicator continued to either increase or decrease, with the magnitude of each change being a value chosen at random from the range ± 1 to ± 20 units. After an indicator reached its maximal (187) or minimal (105) value, the indicator no longer changed until it was reset by the subject pressing the button corresponding to that indicator. (Each button was associated with a single indicator in a consistent 1 to 1 mapping.) Once an indicator was reset it was then restarted at a value close to the middle of the range and began changing again, either increasing or decreasing. The direction of change was random across resets, thus after a reset an indicator could change in the same direction as it had been previously or it could move in the opposite direction.

The analog monitoring task was identical to the digital task in all regards save the manner in which the indicators were presented. (See Figure 2.) The same algorithm was used to determine the rate and direction of change of each indicator, only now the values were used to plot analog representations of these values, with increasing values moving upwards and decreasing values moving downwards. The rates of updating and changing the displays were held constant across the two display types.

For both types of single task visual monitoring trials subjects performed the monitoring task for 60 seconds. The parameters of this task were such that, on average, approximately 35 - 40 indicators would require resetting during the trial if the indicators were reset immediately upon crossing the boundaries. For the dual task trials (Block 2) subjects were first given the target items to study, followed by one min of visual monitoring and then the recall test for the memory task information. The end of the memory task list presentation was followed immediately by the start of the monitoring task, with the only delay being the time needed for the computer to generate the monitoring displays.

Results and Discussion

Performance in the single and dual task trials was evaluated using several dependent variables. For the item recall and location recall condition subjects were given credit for correctly recalling the target information. In the item + location + order condition, performance was measured by scoring both the number of items correctly recalled and the number of locations correctly recalled. For the location measure subjects were given credit for recalling the item's location only if the correct item also appeared in that location. For the analog and digital visual monitoring task we measured the mean reaction time for resetting the indicators and the mean number of errors made per trial, with an error being operationally defined as attempting to reset an indicator before it reached its boundary.

Presented in Table 1 are the mean recall rates for the two single task trial blocks. As expected, on the single task recall trials there were no differences in the performance levels between the analog and digital groups for any of the recall measures (all ps $> .20$). Consistent with the pilot study, the recall rates for the item and location information was significantly better in the item and location conditions than in the item + location + order conditions, and this held for both the analog and digital groups ($p < .05$). (All effects called significant were assessed using appropriate statistical measures and had p values $< .05$.) This finding indicates that there were different levels of difficulty across the three

recall tasks, with the two tasks requiring memory for a single type of information (i.e., the item and location conditions) producing better performance than the condition that required subjects to retain several different types of information (i.e., the item + location + order condition). Thus subjects in the two visual monitoring groups were performing at an equivalent level on the single task recall trials and the item and location recall tasks produced better performance levels than the item + location + order task.

An important point to note with regard to the recall data is that the performance levels were stable across the two blocks of trials. None of the recall conditions showing a significant change in mean correct recall from Block 1 to Block 3. Furthermore, this stability in performance levels is not simply due to a ceiling effect in the item and location conditions: Performance levels in the item + location + order condition were at approximately 70% correct recall. Despite there being considerable room for an improvement in recall, there was no evidence of a change in performance levels across the session.

Finally, although the performance levels on the item trials was numerically greater than that obtained on the location trials, this difference was not significant (1p0 > .10). This suggests that when subjects were only required to perform the memory task, they produced equivalent performance levels in the tasks designed to tap either spatial processing (i.e., the location condition) or verbal/linguistic processing (i.e., the item condition). This suggests, then, that these two tasks are roughly equivalent in terms of their "difficulty".

The results from the single task visual monitoring trials are presented in Table 2. Replicating Hanson et al (ref. 9), the digital task produced significantly longer reaction times than the analog task. There were also significant differences in the errors rates across these two conditions, with the analog condition producing the higher error rate. The differences in reaction times and error rates would seem to indicate that these results represent a classic case of a simple speed-accuracy tradeoff. However, observations of subjects performing these tasks, as well as subjects' introspective self reports, suggest that this was not the case in the present experiment.

Recall that in this task an error corresponds to the subject attempting to reset an indicator prior to its crossing the boundary. Subjects in the analog condition seemed to be making errors because they were attempting to "predict" when an indicator would cross the boundary. However, because the magnitude of the increment/decrement on each update of an indicator was random, these predictions could not be 100%

accurate. Thus as a result of using this prediction strategy subjects occasionally attempted to reset an indicator before it had crossed the boundary. Note, however, that the use of this prediction strategy requires that subjects selectively attend to the indicators that were nearing the threshold for resetting. This selective attention strategy is possible only if the subjects were efficient at monitoring the relative positions of all eight indicators.

In contrast to the analog condition, subjects in the digital condition were quite slow in resetting the indicators. Furthermore, these subjects did not make many "prediction" errors. This low error rate seems to be due to the fact that subjects were unable to efficiently discern which indicators were nearing the boundaries. Subjects in the digital condition did not appear to be able to focus attention on the indicators that were nearing the boundaries and hence they produced long reaction times and low error rates.

Another aspect of the single task reaction times that warrants notice is the fact that subjects' reaction times continued to improve across the session. This suggests that subjects had not reached asymptotic performance levels and thus the processes involved in monitoring the displays had not become "automatic" processes. Based on the distinction of automatic vs. controlled processes (cf. refs. 34, 35) the visual monitoring task still required capacity/resources for its completion. To determine the nature and extent of the capacity/resources required to perform these tasks we need to examine the performance levels in the dual task trials from Block 2.

The mean recall levels for the dual task trials are presented in Table 3. These data indicate that the recall levels in the dual task trials were very similar to those observed in the single task trials (see Table 1). This suggests that subjects were allocating sufficient capacity/resources to the memory task in the dual task trials so as to maintain dual task performance at the level of the single task trials.

A second interesting aspect of the dual task recall data is that there was no evidence of selective interference between the analog and digital monitoring tasks and the three types of recall task. That is, while there were significant differences between the item and location conditions vs. the item + location + order condition, the differences were of approximately the same magnitude for the two types of monitoring tasks. This lack of a memory task x visual monitoring task interaction raises the issue of whether, as predicted by some multiple resource models, there was selective interference in the performance levels of the visual monitoring tasks.

The mean reaction times and error rates for the visual monitoring dual task trials are presented in Table 4. As in the single task trials, there was a significant main effect of visual monitoring condition in both the reaction time data and the error rate data. The analog condition produced shorter reaction times and higher error rates. More importantly, however, there was no evidence that performance on either of these tasks was affected by the type of information subjects had encoded prior to beginning the visual monitoring task. Although the results of the pilot study indicated that performing the item and location memory tasks requires the use of verbal and spatial codes, respectively, there was no indication that maintaining these codes in short term memory interfered with performance on the analog and digital visual monitoring task. This finding offers no support for the notion of separate processing resources corresponding to verbal/linguistic and spatial codes or processes.

General Discussion

One of the goals of this study was to examine the relative difficulty of monitoring analog and digital displays. The results of the present experiment are consistent with those reported by Hanson et al (ref. 9) demonstrating that analog displays are monitored more efficiently than are digital displays. One question that can be asked of these findings is the extent to which they generalize to trained pilots performing actual flight operations. The results of a recent study by Koonce, Gold, and Moroze (ref. 36) indicate that the analog superiority obtained with college students performing our laboratory task is also obtained when both college students and pilots "fly" a flight deck simulator. Koonce et al had flight naive and experienced pilots perform basic flight maneuvers using either analog or digital displays. They found that for both subject populations the analog displays resulted in superior performance to the digital displays. Thus three separate studies provide converging evidence that analog displays are monitored more efficiently than are digital displays.

A second goal of our study was to examine the attentional requirements of monitoring the analog and digital displays. Recall that Hanson et al (ref. 9) used visual monitoring tasks similar to those used in the present study. Those researchers examined the amount of capacity required to monitor the two types of displays by using a nonverbal, auditory secondary task. Koonce et al included a condition in which subjects "flew" the simulator while also performing an aural secondary task (detecting specified patterns of digits). Using these online secondary tasks, both studies found evidence of better secondary task performance with the analog displays than the digital displays. This suggests that when auditory, online

secondary tasks are used there is a difference in secondary task performance as a function of the type of visual display employed.

In the present experiment we employed a memory preload technique to assess the capacity/resource demands of the visual monitoring task. This secondary task required subjects to maintain different types of cognitive codes in short term memory for the duration of the visual monitoring task. Under these conditions we found no evidence of a difference in secondary (or primary) task performance as a function of the specific type of primary and secondary tasks. One of the questions that remains to be answered is why different patterns of secondary task performance were obtained in these three studies.

There are several differences between the procedures used by Hanson et al and those employed in the present experiment, and even greater procedural variations between the study of Koonce et al and our experiment. Based on the available data it is not possible to identify the precise cause of the different patterns of secondary task results. One possible explanation is that perhaps the modality of the secondary task is crucial (we used a visual task whereas Hanson et al and Koonce et al used an auditory task). Alternatively, perhaps the online and preload techniques are not equivalent in the extent and nature of the information processing load they impose upon the subjects. Research ongoing in our laboratory is attempting to resolve these and other issues related to the general goal of providing an accurate characterization of the attentional demands of various visual and auditory information processing tasks.

Finally, in keeping with the goals of the Mental State Estimation Workshop, there are two additional points that we would like to make. The first concerns the implications of the present study for attentional theory. It is important to note that our study was designed to test one instantiation of a multiple resource model, namely a model that postulates different resources for spatial and verbal/linguistic processes or codes. Although our results provide no evidence for this model, it would be premature to discard either the specific multiple resource model we tested or the more general theoretical concept of multiple resources. In terms of the specific model, it is possible that our procedures simply did not stress the subjects information processing system sufficiently to produce the selective interference predicted by the spatial vs. linguistic distinction. Regarding the general theory, it is possible that there are in fact multiple resources, but that the spatial vs. linguistic dimension is not one of the bases for these different processing resources.

The second point we would like to make concerns mental state estimation research. We believe that in order for researchers to relate mental states (as indexed by physiological indices obtained while subjects are engaged in cognitively demanding tasks) to behavior (i.e., the performance observed on these tasks), it is essential that the investigators fully understand the cognitive processes operating when subjects perform these tasks. Mental state estimation researchers and investigators interested in developing models and theories of human information processing could both profit from collaborative research aimed at relating mental states, cognitive processes, and behavior. Such a collaborative, interdisciplinary approach will greatly help to advance our understanding of how people perform various real world tasks of interest.

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Table 1

Mean Recall Levels for the Item, Location and Item + Location + Order Trials in the Single Task Conditions of Blocks 1 and 3

Group	Item	Location	Item + Location + Order: Item Scoring	Item + Location + Order: Location Scoring
		Block 1		
Analog Monitoring	5.36	5.50	4.47	3.97
Digital Monitoring	5.25	5.64	4.58	4.22
Mean	5.31	5.57	4.53	4.10
		Block 3		
Analog Monitoring	5.33	5.72	4.56	3.92
Digital Monitoring	5.36	5.64	4.75	4.39
Mean	5.35	5.68	4.65	4.15

Table 2

Mean Reaction Time (RT) and Error Rates for the Analog and Digital Monitoring Groups in the Single Task Trials of Blocks 1 and 3

Group	RT (in sec.)	Error Rate
	Block 1	
Analog Monitoring	2.59	9.11
Digital Monitoring	5.29	2.80
	Block 3	
Analog Monitoring	2.10	5.93
Digital Monitoring	3.41	3.72

Table 3

Mean Recall Levels for the Item, Location, and Item + Location + Order Trials in the Dual Task Conditions of Block 2

	Recall Condition			
			Item + Location + Order	
Group	Item	Location	Item Scoring	Location Scoring
Analog Monitoring	5.37	5.22	4.76	4.20
Digital Monitoring	5.41	5.59	4.67	4.29

Table 4

Mean Reaction Time (RT) and Error Rate for the Analog and Digital Monitoring Tasks in the Dual Task Trials of Block 2

	Recall Task		
Group	Item	Location	Item + Location + Order
Analog Monitoring			
RT (in Sec.)	2.34	2.39	2.31
Error Rate	5.68	5.55	6.59
Digital Monitoring			
RT (in Sec.)	3.85	3.72	3.94
Error Rate	3.52	3.17	3.72

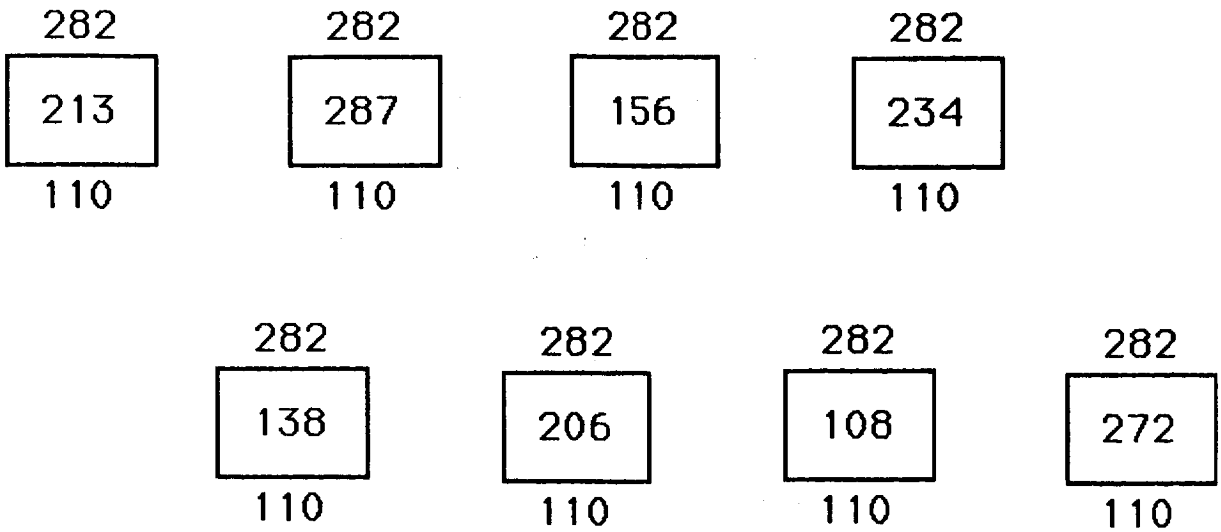

Figure 1. Example CRT Display for the Digital Visual Monitoring Task.

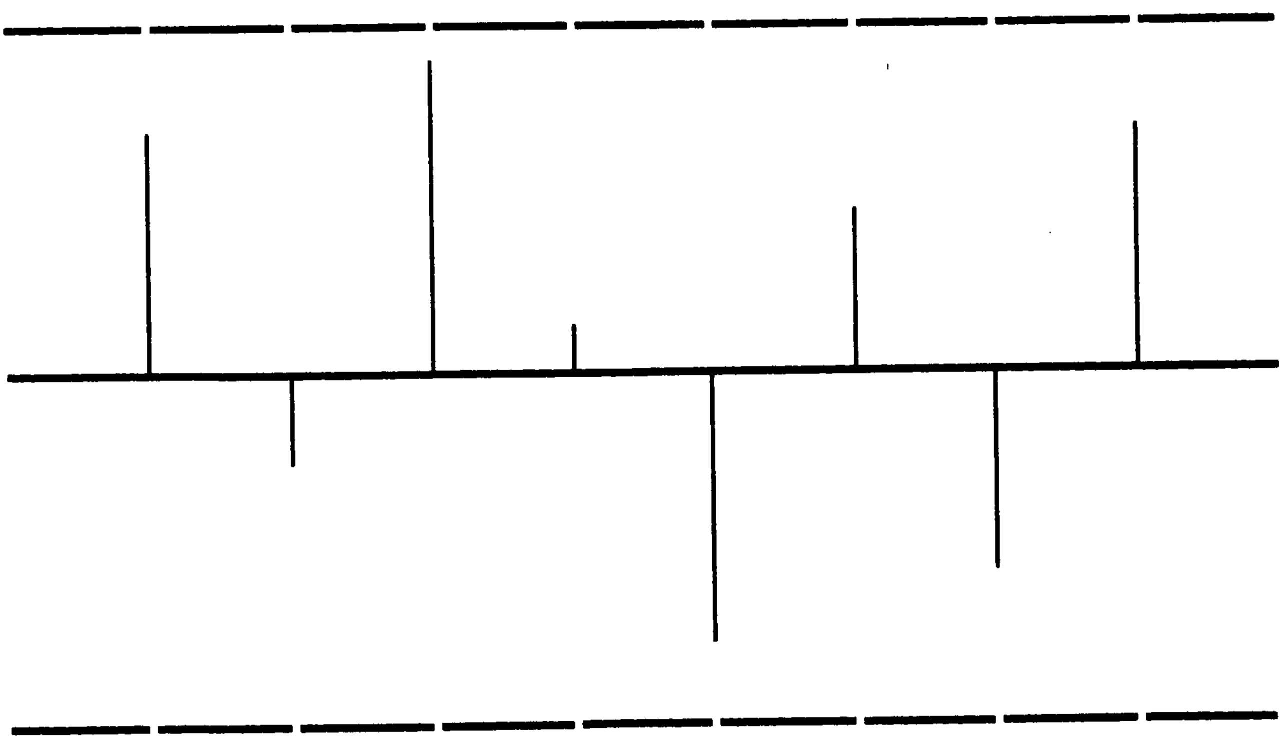

Figure 2. Example CRT Display for the Analog Visual Monitoring Task.